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Research on a new generation of Cherenkov counters

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Abstract

Experimental results with a Parallel-Plate Avalanche Chamber (PPAC) having a CsI photocathode and pad array read-out are reported. High gains in excess of 10^5 have been obtained with He gas at atmospheric pressure and traces of CH_4 or CF_4 quencher. Such light gas mixtures extend the transparency for the Cherenkov light to the extreme UV region and allow detector operation with very low sensitivity to the ionization produced by minimum ionizing particles. A Hadron Blind Detector (HBD) is discussed which exploits the broad photon energy bandwidth (≈ 10 eV) and the high Cherenkov threshold ($p_\pi = 15$ GeV). This fast detector since it has a good spatial resolution, can be used at the future Large Hadron Collider (LHC) or the Superconductivity Super Collider (SSC) either as an efficient electron tagger, rejecting hadrons faking electrons in the calorimeter, or as a pre-tracker giving fast electron and high-energy muon signature and momentum estimation. Other potential applications in the domain of Cherenkov light detection are also discussed.

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1 Introduction

Cherenkov radiation detectors for particle identification (threshold counters) [1], velocity determination (differential counters) [2], or Cherenkov angle measurement (Ring Imaging Cherenkov (RICH) detectors) [3], are widely used in high-energy physics. Their spectral sensitivity, limited in the ultraviolet (UV) region by the transmission cut-off of the window material, often leads to a small detectable Cherenkov light yield. Low light yield appears to be an even more serious problem when the highest momentum threshold, and therefore the lowest gas refractive index (He) are required, unless one makes use of very long radiators. Cherenkov He radiators about 10 m long have already been used in particle physics. This is feasible for counters operating in the visible light region where absorption is negligible. When operation in the UV is required, special care should be taken to avoid absorption losses. As an example, RICH counters [4] operate in the far UV between 200 and 145 nm, a region where the oxygen and water absorption cross section are large about 10 Mbarn. In spite of these difficulties, a 20 m He-based RICH detector has been operated for particle identification in the Fermilab E-605 experiment [5].

A way to increase the detected photoelectron yield and reduce the size of the radiator is to extend the spectral sensitivity to the far UV region by using expensive and delicate LiF windows. However, another approach consisting of windowless threshold Cherenkov counters has recently been proposed [6]. In the new concept the same gas is used as radiating medium and for high-gain multiplication. This kind of detector is called Hadron Blind (HBD) because of its ability to select leptons by rejecting low-momentum hadrons. This principle can be extended to particle identification in the Cherenkov threshold mode at high energies.

An HBD detector is shown schematically in Fig.1. Cherenkov photons produced in a gas radiator extract electrons from a solid photocathode made by CsI deposited on a metallic substrate. [7]. Photoelectrons are then amplified and detected by either a Parallel Plate Avalanche Chamber (PPAC) or by a more conventional multiwire proportional chamber [8]. In both cases, because of the small effective gap of the detector and the use of low-Z gases based on He mixtures, the background due to the direct ionization of the charged particles is negligible. Rejection of a factor 100 have been predicted against undesirable low momentum particles. Rejection of low-momentum hadrons ($p=5-20$ GeV/c) is crucial at the Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC) for efficient electron detection. It is now well established that the good electron identification obtained with calorimeters, in single-particle test-beam, is limited by gammas spatially overlapped with soft charged hadrons and faking, therefore, electrons in high-energy hadronic events [9].

In a second configuration HBD detectors can be used as fast pre-trackers system inside a magnetic field to select and measure momentum quadrivectors of electrons and high p_t muons at an early trigger level [10]. The fast momentum estimation is compared with the one obtained from the calorimeter to reject gammas faking electrons and with that from the external muon stations to reject punchthrough and part of the hadron decay muons. In all these evaluations an important benefit, as a result of the low momentum particle rejection, is the clean event patterns, especially in the central region of a LHC experiment, as well as in the future heavy ion experiments where the overloading of the detectors because of the high multiplicity constitute a serious problem.

Although He mixtures with hydrocarbons was demonstrated to allow reaching of high gains necessary for single electron detection [11], the bandwidth for the Cherenkov light production is limited by the relatively low photon energy transmission cut-off due to the hydrocarbon component (He itself is transparent for photons up to about 20 eV). In a He+CH₄ gas mixture the useful band-width defined between the quantum efficiency threshold of the CsI photocathode and the transmission cut-off of CH₄, is about 2.5 eV. A possibility to extend the detected photon bandwidth is to use H₂ as quencher, since hydrogen is transparent up to 12 eV and the photocathode quantum efficiency is higher in this wavelength range. Compared to the result with a He + CH₄ mixture the number of detected photons is then expected to be 5 times higher. Another idea to further enlarge the band width is to use very small quantities, i.e traces of quencher; under the constraint that at the same time the detector could be operated at high gains.

This latter idea has recently been developed and tested in the laboratory. Preliminary experimental results are presented in the next section.

2 Experimental set-up

Laboratory tests were performed using a PPAC consisting of a cathode segmented into 5x5 mm² rectangular pads and an anode mesh (Fig.2). The distance between anode and cathode is 4 mm, the diameter of the wire in the anode mesh is 50 μ m with a 500 μ m pitch. Cathode pads are made using a standard printed-circuit technique, etching 25 μ copper layer on a fibreglass substrate 2 mm thick. Metalized holes through the substrate permit connection to the electronic chain mounted on the back side. The entrance window is realized with a 10 mm thick BaF₂ crystal, used for the calorimetry studies [12].

A solid CsI layer 1000 nm thick was deposited on the pads by vacuum evaporation; a special vessel was used to deposit the photocathode and flush it with vapors of ethyl ferrocene and to form a thin adsorption thin layer on it. It has already been observed that a thin adsorbed layer of such a substance prevents CsI degradation caused by the contact with oxygen and water. The total exposure in air of the photocathode during its transportation and mounting in the chamber was estimated of about 1 hour; after assembly the chamber was flushed for several days with CH₄, purified through an oxysorb cartridge, before performing measurements.

The described PPAC was used to test the operation of the photodetector in high gain conditions. A pulsed hydrogen lamp is used as a source of UV photons; the UV light emitted can be collimated by a series of calibrated light attenuators allowing to reduce the amount of incident light at the desirable level down to single photon.. The lamp-attenuation system is mounted on rail allowing to scan the pad detector in the X-Y plane with a precision of 100 μ m.

Signals induced on the cathode pads during the avalanche process are amplified by low- noise preamplifiers having a sensitivity of 200 mV/pC. Sets of 24 such preamplifiers are mounted on cards and then connected by appropriate pins to individual pads in a row. The electronic noise of each preamplifier was measured to be $\approx$ 300 electrons before connection with the detector; during operation the noise increased to around 1500 electrons rms, still an acceptable value. Each channel is read-out by charge sensitive analog-to digital converters (ADCs) (2249-W Lecroy) gated by a fast signal generated in coincidence with each flash of

the UV lamp.

3 Experimental results

At first, signals were obtained, exciting the photocathode with the full UV lamp intensity, while the chamber was operating in ionization mode. A typical signal as seen with a digital oscilloscope is shown in Figure.3. The-rise time, 200 ns, is compatible with the total drift time expected in a mixture of He + 1% CH₄. The collected charge is about 100 times more than the one measured when extracting electrons from the untreated copper pads, thus showing the beneficial effect of the CsI on the quantum efficiency of the photocathode. Although this measurement excludes gross defects of the CsI photocathode, the determination of its absolute quantum efficiency could not be verified with the present apparatus. We should also mention that with the chamber operated in the ionisation mode the signal decreases by about 40 % when CH₄ is replaced by He. This effect has been already observed with argon [7] and attributed to backscattering of electrons from argon. However there are indications that the loss is recovered at higher electric fields where amplification occurs, due to larger extraction field.

The high voltage is then increased and electron avalanche multiplication is observed in the parallel plate mode. The gain is determined as the ratio of the collected charge during multiplication to the one obtained in the ionization mode. Figure. 4 shows the detected charge profile measured by scanning along a horizontal row of the pad array of the photodetector. The uniformity is better than 20 %, satisfactory for the HBD project. The small inhomogeneities observed can be due either to a non uniform deposition of the CsI layer, or to differences in the electronic gains.

Mixtures of He with a few percent CH₄ have often been used for single electron detection; large gains of about 10⁶ have been reported using wire chambers or PPACs at low or atmospheric pressures. We performed tests using a He mixture with small concentration of CH₄. The He gas was purified through an oxysorb filter, which removes mainly O₂ and water at the level of 1 ppm. Figure.5 shows the gain as a function of applied high voltage using only 0.8% of CH₄ as quencher. Large gains can be obtained for concentrations as low as 0.1% of CH₄, but below this value the operation of the chamber becomes unstable. With such a small amount of CH₄ the transmission cut-off moves from 145 nm to about 137 nm enlarging the useful bandwidth and doubling the number of detected Cherenkov photons.

An important improvement was obtained by replacing CH₄ by CF₄ as quencher. Gain measurements with this mixture are shown in Figure.6, for various concentrations of CF₄ from 4% to 0.3%. The gain is still high at 3 per mille admixture level and there is some evidence that the gain remains high at even lower concentrations. This quite unexpected experimental effect is accompanied by a drastic reduction of the required electric field to achieve high gain operation. It is certainly evidence of strong Penning effect [13]. In low CF₄ concentrations inelastic collisions occurs between the avalanche electrons and He atoms, which are therefore excited or ionized, the excitation probability being important at low electric fields. A resonant effect, perhaps due to the high ionization potential of CF₄ (≈16 eV), enables the transfer of the excitation energy of the He atoms to the CF₄ molecule by the following process :

The PPAC operation at high gain regime with only traces of CF_4 is a suitable way to enlarge the Cherenkov photon acceptance in the HBD detector, since CF_4 at the level of a few per mille is transparent up to 12 eV (the photon mean free path is 30 cm at 12 eV, where the photoabsorption cross section is 400 Kb [14]). The above experimental evidences allow HBD counters to cover a huge wavelength region which has never been explored by conventional systems, extending from the near UV to extreme UV; a consequence is the increase of the number of Cherenkov photons detected and we can take full advantage of the very high photocathode quantum efficiency in this wavelength range. This important improvement could permit HBD operation at a high momentum ($P=16 \text{ GeV}/c$) threshold with reasonable size of the radiator dimension. Taking into account the measured CsI photocathode quantum efficiency and the transparency of CF_4 we expect 6 photoelectrons to be detected with a 50 cm long He radiator. However, there are discrepancies by a factor of two between measurements of the CsI absolute quantum efficiency [15]. If the low value is finally confirmed we can still avoid increasing of the radiator length by either raising the gas pressure or by using higher refractive index gases. As an example, Ne seems to be a good candidate and this should be investigated.

In another experiment the detected signal was reduced in order to get an average of 0.4 photoelectrons produced per pulse of the UV lamp. Such a signal simulates the expected parasitic pulses, produced by minimum ionizing particles (mip) with momenta below the Cherenkov threshold because of the contribution of the ionisation process ($\approx 0.15 \text{ e/mip}$) in the small active detector gap and secondary electrons from the photocathode (0.2 e/mip) [6].

The single electron pulse height obtained is shown in Figure.7 and it is compared with the one corresponding to 10 photoelectrons produced in average per flash, which simulates the signal expected from a high energy electron producing Cherenkov light inside the radiator of a HBD detector. The overlap of the two curves is quite low, and by adjusting the discriminator at the level of 10 ADC bins (2.5 pC) the efficiency for the 10 photoelectron signal is close to unit, while the threshold limits the parasitic pulses to a probability of smaller than 1%. It provides a rejection factor better than 100 against the unwanted low momentum hadrons in a real experiment, as calculated taking into account the distribution of ionisation electrons produced in pure He. If this laboratory result is confirmed in a particle beam test, the HBD will constitute an excellent electron tagger superior to the Transition Radiation Detector (TRD).

4 Future improvements

A systematic study of aging properties of the CSI photocathode has been performed [16]. Under clean gas conditions (oxysorb filter + stainless steel for the gas tubing), no degradation was observed up to collected charge of $100 \text{ mC}/\text{cm}^2$. This value can dramatically decrease if no care is taken about the gas purity; but, even in this case however by warming the photocathode at $70 - 80^\circ\text{C}$, practically a full recovery of the initial QE was observed. The laboratory tests have been performed with a $20 \times 20 \text{ cm}^2$ PPAC. One has to analyse the conditions for the construction of larger surfaces. The electrostatic attraction between the electrodes reduces the gap at the center and spoil the field homogeneity which is of paramount importance for uniform amplification. The pad structure permits a correction of

this effect by a method which is envisaged for an improvement program of the spherical drift chambers used for X-ray imaging [17]; pads can be biased by a varying voltage as a function of the distance to the center of the chamber in order to compensate for the variation of amplification.

Another possible improvement of the HBD efficiency can be achieved if a gas separation between the sensitive PPAC zone and the radiator zone can be obtained. Then the region of the sensitivity is extended up to 21 eV, if in the radiator volume only He gas is circulating and the number of recorded photons could be doubled.

This could be obtained by techniques elaborated and used for VUV diagnostics of plasma discharges [18]. In this investigation the emission of photons with energy up to 21 eV was detected through a photosensitive wire chamber separated by the emission volume using two different techniques. In the first a thin colloidal window (100 nm) was attached to a mesh assuring the mechanical strength and serves to separate the two gas volumes. Then different gases are circulated in the two volumes with very small diffusion from one volume to the other. An excellent gas transparency close to 100% was obtained over 20 cm length. In the second one the window was replaced by a special mesh made with indium capillaries having a lot of small holes injecting the photosensitive gas to the detector with high flux (0.5 - 1 litres/sec) and creating a gradient of the photosensitive gas in the volume. With this method a good gas separation between the two volumes was obtained.

This last technique should be certainly taken into consideration and a tentative design of a possible detector is shown in Figure.8. A plane of 100 μm capillaries commercially available with a gap of about 1 mm are used to inject with a high speed (1 m/sec) the He and CF_4 admixture to the pad plane. Small holes on the pad planes are receipting the injecting gas, which is then purified by a cold filter and injected to the radiator volume through a closed circulation system. With such system the gas distribution is expected to be not uniform in space but stable in time in the sensitive region with small contamination of the injected gas in the radiator volume. We should note that an independent work was performed at CERN for the Barrel RICH DELPHI project to attempt a separation of the drift volume and the detector sensitive zone [19]. The idea was to suppress photon feed-back from the wire chamber filled with TMAE vapors. The quoted results give an additional possibility to further extend the sensitivity of the HBD and to reduce of its size. Although these measurements are useful further experimental investigations are required to demonstrate the feasibility of such techniques.

5 Discussion and outlook

The tests made with a PPAC type detector, with pad readout and CsI photocathode are very encouraging. High gain operation has been obtained with the He gas mixed with a few per mille of CH_4 or CF_4 . In particular, a low concentration of CF_4 gas is the most promising because it extends the spectral sensitivity of the system detector and photocathode to the extreme UV region (≈ 16 eV). In addition this detector is almost insensitive to the direct ionization caused by the passage of minimum ionizing particles; it is fast, has good granularity and low material thickness.

All these features open up the way to a wide range of applications in the domain of detection and localization of individual photons. An obvious one is the detection of Cherenkov

light taking advantage of the properties of this detector, especially the broad Cherenkov photon spectral region to which the Cherenkov detector is sensitive. It results in a shorter radiator, by almost one order of magnitude, compared to conventional systems.

In addition to the obvious advantage of this achievement, another important benefit comes from the consequent reduction of the size of the Cherenkov spot light seen by the photodetector, which is of the order of few millimetre in radius and permits the localization of the charged particle producing Cherenkov radiation. Conventional systems are using complex high-cost focusing devices and sometimes concentrators to collect the Cherenkov light, which leads to the loss of the self-localization capability of the detector. The new approach offers the possibility of building efficient trackers, sensitive only to particles above a certain momentum threshold.

Hadron Blind Detectors, selecting high-momentum leptons in high-background environments of the future hadron colliders, could operate with He-based mixtures in high-momentum hadron rejection mode. Laboratory tests, simulating the Cherenkov light cone by a UV collimated light beam exciting the pad photodetector, indicate that large rejection factors of about 100, against low momentum hadrons should be achievable with an HBD detector.

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Figure captions

- Figure 1. Schematic of a HBD module. Cherenkov light is produced by a high energy electron in narrow cone. It produces photoelectrons in the pad - CsI surface, extracted and amplified to the anode plane.
- Figure 2. A shematic view of the photodetector test bench, showing the pad detector with the wire anode plane and its UV window. Ultra violet light produced from a hydrogen flash lamp reaches the pad photodetector through a collimator.
- Figure 3. Typical signal observed, at the output of the charge preamplifier, with a digital oscilloscope. The PPAC is filled with mixture of He and CH₄ and operates in the ionisation mode with 500 Volts applied on the anode. The horizontal and the vertical scale are 50 ns and 10 mV respectively.
- Figure 4. The light beam profile seen by an horizontal row in the pad array. The horizontal scale is the pad number and the vertical one the charge collected.
- Figure 5. Gain obtained as a function of the applied Voltage with He + 1% CH₄.
- Figure 6. Gain versus High Voltage for various mixtures of He + CF₄.
- Figure 7. Pulse height spectrum when the .4 photoelectrons (solid line) and 10 photoelectrons (dashed line) are respectively produced per flash of the lamp.
- Figure 8. Schematic of a HBD module with recirculation gas system through a cold trappe filter with a recirculator. Gas separation is obtained by using a plane of capillary tubes with gas injection.

Figure 1

Figure 2

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Figure 3

Figure 4

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